Author version: *J. Atmos. Ocean. Technol., vol.30; 2013; 379-388*

Observational evidence of summer Shamal swells along the west coast of India

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Abstract

Wave data collected off Ratnagiri, which is on the west coast of India, in 2010 and 2011 is used to examine the presence of the summer Shamal swells. This study also aims to understand variations in wave characteristics and associated modifications in wind sea propagation at Ratnagiri. Wind data collected using Autonomous Weather Station (AWS) along with ASCAT and NCEP data, are used to identify the presence of summer Shamal winds along the west coast of the Indian subcontinent and on the Arabian Peninsula. NCEP and ASCAT data indicate the presence of summer Shamal winds over the Arabian Peninsula and northwesterly winds at Ratnagiri. This study identifies the presence of swells from the NW direction that originate from the summer Shamal winds in the Persian Gulf and that reach Ratnagiri during 30% of the summer Shamal period. AWS data show the presence of NW winds during the month of May and SW winds during the strong SW monsoon period (June-August). Another important factor identified at Ratnagiri that is associated with the summer Shamal events is the direction of wind sea waves. During the onset of the SW monsoon (May), the sea direction is in the direction of swell propagation (NW), but during the SW monsoon (June-August), a major part of the wind sea direction is from the SW. The average occurrence of summer Shamal swells is approximately 22% during the SW monsoon period. An increase in wave height is observed during June and July at Ratnagiri due to the strong summer Shamal event.

1. Introduction

Waves are the dominant factor influencing the near shore processes. The waves along the west coast of the Indian subcontinent primarily depend on the wind conditions prevailing over the three different seasons: southwest (SW) monsoon (June-September), northeast (NE) monsoon (October-January) and pre-monsoon (February-May). The general wave conditions in the Arabian Sea during the pre-monsoon period also depend on the swells coming from the far northwest (NW) Arabian Sea because of the northwesterly blowing Shamal winds (Aboobacker et al. 2011). According to Aboobacker et al. (2011), NW waves are observed along the west coast of India with mean periods ranging between 6 and 8 seconds. These waves are due to the strong northwesterly winds blowing in the Arabian peninsula and the northwestern Arabian sea, and result in increase in wave height, decrease in swell period and common NW direction during the NE monsoon and early pre-monsoon season. During the NE monsoon and early pre-monsoon season, the maximum significant wave height observed is 3.5 metres near the Arabian Peninsula and 2 metres along the west coast of India. Kumar et al. (2010) studied the characteristics of swells and wave growth during the onset of the summer monsoon. Coastal processes along the Indian subcontinent are a function of wave parameters such as wave height, wave period and wave direction. During the Indian summer monsoon (SW monsoon), the dominate swells are from the SW direction because of the strong SW wind. During the Indian winter monsoon (NE monsoon) and the calm pre-monsoon season, the swells observed along the west coast of the Indian subcontinent are from the W and WNW directions and the SW direction, respectively, because of the weak NE winds. The shift in wave direction from SW to NW will change the direction of the longshore drift from south to north along the west coast of India. The present study examines the presence of summer Shamal waves and winds in the near shore region of the Indian west coast. The variation in the existence of summer Shamal swells and wind sea propagation along the west coast of India is studied during the late pre-monsoon (May) and strong Indian summer monsoon (June-August) seasons.

The most well-known weather phenomenon in the Persian Gulf is the Shamal, a NW wind, which occurs year round (Perrone 1979). The Shamal is the only persistently strong wind in the region that can last for several days, have winds that can reach strong to gale force over the open sea and routinely produce wind waves of 3 to 4 metres in height. According to Barth (2000), a high-energy summer Shamal regime occurs from June to August, with a complex transition phase in May, at the Arabian region. A moderate eastern spring phase occurs in April. Membery (1983) found that the summer Shamal is persistent over Iraq and the Gulf during the summer from May to July. Rao et al. (2001) reported that 51% of Shamal days occurred from May to July compared to the winter months of November to March. Aboobacker et al. (2011) used the February data collected from the west coast of India to identify the winter Shamal events occurring at the Arabian Peninsula from November to March and the corresponding swells reaching the Indian west coast. The present study focuses on identifying the presence of summer Shamal winds and swells along the west coast of India. This study will help in understanding the effect of summer Shamal waves and winds on the near shore regions of the Indian west coast. These winds are often strong during the day, but they decrease at night. The summer Shamal events are longer in duration compared to the winter Shamal events. Because of their longer duration, summer Shamal events are also known as "40-day Shamal". The summer Shamal is practically continuous from early June through July, and it is associated with the relative strengths of the Indian and Arabian thermal lows (Reynolds 1993).

2. Study area

The wind and wave data measured at Ratnagiri (Figure 1) were used in the study. The measurement location lies along the west coast of the Indian subcontinent. The Arabian Peninsula and the Persian Gulf are located on the north east of Ratnagiri. The wave climate of the Arabian Sea and the climate along the west coast of India are influenced by the monsoonal winds during the SW monsoon with high wave activity. A relatively calm condition prevails during the rest of the year. The direction of approaching waves is W and W-SW during the SW monsoon, W and W-NW during the NE monsoon and SW during the fair weather period (Kumar et al. 2006). The sea breeze has an impact on the diurnal cycle of the sea state along the west coast of India during the pre-monsoon season because of the weak winds (Neetu et al. 2006).

3. Data and Methodology

Waves off Ratnagiri at a water depth of 13 metres (16^{o} 58’ 48.324” N and 73^{o} 15’ 30.312” E) were measured using a moored Datawell directional wave rider buoy DWR-Mk III (Barstow and Kollstad, 1991). The wave rider buoy measures heaves in the range of -20-+20 metres and periods between 1.6 and 30 seconds, with a resolution of 1 cm in heave. The cross sensitivity of the heave is less than 3%. The measurement of the wave direction using DWR Mk-III is in the range of 0-360^{o} and a resolution of 1.5^{o}, with an accuracy of 0.5^{o} reference to the magnetic north. Data were recorded for 30 minutes at a frequency of 1.28 Hz every half hour from May 1 to August 31 in 2010 and 2011. The collected time series was subjected to standard error checks for spikes, steepness and constant signals (Haver 1980). The wave data analysis was similar to that reported in Kumar et al. (2010). Wave spectra were obtained through Fast Fourier transform (FFT). A FFT of 8 series, each consisting of 256 measured vertical elevations of the buoy data, were added to obtain spectra with a high-frequency cutoff at

0.58 Hz and a resolution of 0.005 Hz. The significant wave height (Hs), or $4\sqrt{m_o}$, and the mean wave period (Tm), or $\sqrt{m_0/m_2}$, were obtained from the wave spectrum. Whereas m_n is the n^{th} order spectral moment and is given by $m_n = \int_0^\infty f^n S(f)df$, n=0 and 2, S (f) is the spectral energy density at frequency f. The period corresponding to the maximum spectral energy (i.e., spectral peak period (Tp)) was estimated from the wave spectrum. Peak wave direction (Dp) corresponding to the spectral peak was estimated based on circular moments (Kuik et al. 1988). The meteorological convention is used for presenting the wind and wave direction data (0 and 360° for wind/wave from North, 90 for East, 180 for South, 270 for West).

Wind seas and swells from the measured data were separated through the method described by Portilla et al. (2009). Portilla et al. (2009) proposed a 1-D separation algorithm based on the assumption that the energy at peak frequency of a swell system cannot be higher than the value of a PM spectrum (Pierson and Moskowitz, 1964) with the same peak frequency. The algorithm calculates the ratio (γ^*) between the peak energy of a wave system and the energy of a PM spectrum at the same frequency. If γ^* is above a threshold value of 1, then the system is considered to represent the wind sea; otherwise, it is taken to be swell. The wind sea and swell components of significant wave height, mean wave period and mean wave direction were computed by integrating the respective spectral parts. Resultant or total is the estimated values, without separation into wind sea and swell.

Simultaneous wind measurements were carried out using the Autonomous Weather Station (AWS) at 10-minute intervals. The AWS measures the wind speed in the range of 0-60 m/s with an accuracy of 0.2 m/s and a direction from 0 to 360^o with an accuracy of 3^o. AWS data were used to analyze the wind pattern of Ratnagiri in 2010 during strong and weak summer Shamal winds. Because of the unavailability of AWS wind data during 2011, these data were not used in the study. AWS wind data are useful for understanding the variation in wind speed and direction associated with the summer Shamal wind, local wind system (sea breeze and land breeze) and SW monsoon winds during strong and weak summer Shamal events.

Reanalysis data of zonal and meridional components of wind speed at a height of 10 metres, real-time observations at 6 hour intervals from NCEP / NCAR (Kalnay et al. 1996) and daily data from ASCAT wind (Verhoef et al. 2012) obtained over the Arabian Sea and the Persian Gulf were also used to analyze the wind pattern. The NCEP / NCAR data were provided by the NOAA-CIRES Climate Diagnostics Center in Boulder, Colorado. These data can be found at http://www.cdc.noaa.gov/. The ASCAT data are derived from the ASCAT scatterometer onboard EUMETSAT Metop-A satellite and are downloaded from the PO.DAAC.ASCAT. The data are used to calculate the relative wind strength between the summer Shamal wind at the Persian Gulf and SW winds off Somalia because of the daily average data with high spatial resolutions of 50 kilometers. NCEP data are used to analyze and study the combined effect of NW summer Shamal winds and SW Indian summer monsoon winds over the Arabian Sea. This analysis will give a good indication of the temporal variation of summer Shamal events at the Persian Gulf and its propagation over the Arabian Sea.

4. Results and discussion

   a. Wind pattern over the Arabian Sea

ASCAT wind data are used to study the presence of weak and strong Shamal and SW monsoon winds. For this purpose, we used the average wind speed and direction obtained from three boxes: (1) near the Arabian Peninsula (B1), (2) near the north east of the African continent (B2) and (3) near Ratnagiri (B3). The ratio between the daily average wind speeds near the Arabian Peninsula at B1 to the SW monsoonal winds at B2 is used to estimate the relative strength of winds between the summer Shamal and SW monsoon winds. Occurrences of summer Shamal swells at Ratnagiri depend on the comparative strengths of these wind systems. The combined effect of NW Shamal winds and SW monsoon winds along the study region were examined based on the B1/B2 value and were characterized as summer Shamal winds and weak SW winds when the B1/B2 value was greater than 1.0 and summer Shamal winds and strong SW winds when the B1/B2 was less than 1.0 for NW winds blowing over the Persian Gulf region. The correlation coefficient between the Shamal winds and winds at Ratnagiri during the Shamal events is 0.16. This coefficient indicates the near absence of summer Shamal winds at Ratnagiri due to the strong SW monsoon season in the Arabian Sea. NCEP data are used to study and analyze the change in wind pattern over the Arabian Sea near the west coast of India and over the Arabian Peninsula during the summer Shamal event.

(i) Summer Shamal winds and weak SW winds

Figure 2 depicts the composite average of the wind pattern over the Arabian Sea, under the combined effect of the strong NW summer Shamal and the weak SW Indian summer monsoon winds, in 2010 and 2011. Six hourly averages of NCEP data over the Arabian Sea during summer Shamal winds and weak SW monsoon winds (Figures 2a, 2b) indicate the presence of NW summer Shamal winds over the Persian Gulf and the Arabian Peninsula. When the summer Shamal dominates over the weak SW monsoon, SW winds from the south western Arabian Sea are deviated by the NW winds from the

Arabian Peninsula and propagate towards Ratnagiri as W-NW winds. The change in wind direction depends on the strength of NW winds, and it has enough strength to reach the west coast of India as NW winds. This condition mainly prevails over the Arabian Sea during May.

(ii) Summer Shamal winds and strong SW winds

Figures 2c and 2d depict the composite average map of NCEP wind over the Arabian Sea during different periods of the strong SW Indian summer monsoon. During this period with a strong SW monsoon, Shamal winds dominate the Arabian Peninsula and the Persian Gulf region. The wind pattern over the Arabian Sea is driven by the SW monsoonal windswith the small variation in the direction of NW winds toward the north that are observed at the Arabian Peninsula. This phenomenon is due to the interaction between northwesterly and southwesterly winds and mainly prevails during June, July and August when the B1/B2 value is less than 1.0.

b. Wind pattern over the Arabian Gulf

Figure 5 depicts the wind pattern over the Persian Gulf using the data derived from the wind scatterometer ASCAT. The wind direction during May and June indicates the presence of summer Shamal (NW winds) events. The summer Shamal events persisted over the Persian Gulf for about 10 days (Figure 5a) during 2010, whereas in 2011, the summer Shamal events had a longer duration, starting in late May and persisting for more than 20 days (Figure 5b). The wind direction also showed a more consistent pattern from the NW side, indicating the summer Shamal events at the Persian Gulf where the summer Shamal swell originated. The correlation between the B1/B2 ratio and wind direction time series showed a positive correlation of 0.40 and 0.38 during the summer Shamal period of 2010 and 2011, respectively.

c. Winds along the west coast of India

The AWS wind data at Ratnagiri in May (Figure 4a) show that during the onset of the SW monsoon period (May), the wind is predominantly from the NW direction. During this period, the NW wind from the Arabian Peninsula shows the continuous arrival of wind, without the presence of a land breeze, during the night in the pre-monsoon (May). Aboobacker et al. (2011) observed the presence of NW winds during the winter due to weak NE winds. In May (pre-monsoon period), SW winds are weak, and NW winds are strong enough to affect the near-shore regions of Ratnagiri and cause wind sea from the NW direction. AWS wind data during June (Figure 4b) show that during this period, the wind is predominantly from the SW direction, indicating the presence of SW winds at Ratnagiri. This wind will cause the generation and propagation of wind sea either from the NW or SW direction depending on the direction of the winds blowing over the near-shore area of Ratnagiri.

Figure 6 indicates that a summer Shamal wind over the Persian Gulf shows a wind propagation period of 2-3 days to reach the coast of Ratnagiri during peak time. The low correlation coefficient of 0.21 obtained between the wind direction at the Persian Gulf and the wave direction at Ratnagiri during the study period indicates that the wind direction at Ratnagiri is primarily influenced by the strong SW monsoon seasonal winds in the Arabian Sea.

d. Existence of summer Shamal swells

Figures 7-8 depict the presence of NW Swells reaching the Indian coastline at Ratnagiri during the summer Shamal period between May and August in 2010 and 2011. The NW swells show stronger Shamal events during the summer of 2011 than those in 2010 at the Arabian Peninsula. The measured waves during May 2010 (Figure 7a) and 2011 (Figure 8a) show a steady decrease in swell direction toward the Indian summer monsoon. This change in swell direction from NW to WNW occurred during May and continued in the WNW direction in June and July. This continuation occurred because of the interaction of waves from the NW swells produced by the summer Shamal events and SW swells owing to the strong SW monsoon over the Arabian Sea. The presence of strong summer Shamal swells in May is due to the weak SW monsoon winds during the onset of the summer monsoon. After the summer monsoon, there is a decrease in the number of swells coming from the NW sector due to the dominance of swells from the SW Indian summer monsoon. The SW swells have higher amplitudes compared to the NW swells. During 2010 and 2011, an absence of NW swells was observed during the weak NW winds at the Arabian Peninsula due to the strong SW winds of the Indian summer monsoon and the rough sea state of the Arabian Sea. The swells propagating from the Persian Gulf travel approximately 1200-1500 kilometres to reach the Ratnagiri coast (Aboobacker et.al. 2011). This will trigger a time difference between the arrival of summer Shamal swells and winds at Ratnagiri. The correlation between Ratnagiri wind and waves is 0.61.

Contours of wave direction in a Frequency-time domain (Figure 9) during May of 2010 and 2011 show the NW swells reaching the near-shore area of Ratnagiri. Periods of NW swells ranged between 6.5 and 11 seconds, and the swell direction was up to 315°. The increase in swell period is associated with the decrease in swell direction due to the onset of the strong Indian SW monsoon season. Figure 9 also shows the presence of long period swells dominate in the range of less than 240° from the SW direction. At the end of May, the swells from the SW are dominant throughout the Arabian Sea because of the break in the summer Shamal winds and the strong Indian summer monsoon.

e. Wave characteristics

The measured waves at Ratnagiri in 2010 and 2011 from May-August show the presence of NW swells during a particular interval, in contrast to the normal condition of SW waves. The swells during May show an increase in wave height and a decrease in wave period similar to the winter Shamal swells along the west coast of India (Aboobacker et al. 2011). The direction of the swell and resultant waves shows a shift in the wave direction toward the west from the NW direction during June and July compared to May. The direction of the wind sea depends on the wind condition along the west coast of India. Therefore, the direction of the wind sea in the first half of May is from the NW, and during the remaining period, the direction shifts from NW to W and then to the SW, depending on the strength of the winds reaching the west coast of the Indian subcontinent. During the strong SW monsoon period (June to August), the direction of the wind sea is mainly from the SW direction.

During the period when the summer Shamal swells reach the west coast of India at Ratnagiri, the mean wave period is in the range of 3.7 to 7.7 seconds (Tables 1 & 2), with the mean swell period in the range of 6.6-11.2 seconds. Significant wave height varied between 0.7 and 1.7 metres during May, and during the SW monsoon period, significant wave height increased and varied between 1.4 and 3.4 metres. This increase in wave height during June is also due to the strong northwesterly winds from late May to early July (Membury 1983). The swell direction is more than 270° and reaches up to 308° 30% of the time. However, the wind sea shows both a SW and NW direction, depending on the prevailing wind condition along the west coast of the Indian subcontinent.

f. Interaction between SW swells and NW swells in the Arabian Sea

The propagation of swells from the NW Shamal event is smooth, and continuous detection of these swells is possible along the west coast of India. The swell direction is well above 270°. However, during the SW monsoon, the directions of observed NW swells show a decrease in wave direction and are just above 270°. The decrease in wave direction from NW to WNW is due to the interaction of swells between the NW and SW direction (Aboobacker et al. 2011). The observed direction of NW swells in May clearly indicates the decrease in wave direction with the increase in Indian summer monsoon conditions.

g. Effect of summer Shamal swells along the Indian coast

Because of the NW-SE inclination of the coastline, the swells propagating from NW will change the alongshore current and sediment transport regime towards south from the prevailing northerly direction. This change in near-shore currents and the sediment transport from north to south depends on the strength of the Shamal swells and Shamal events at the Arabian Peninsula together with the prevailing summer monsoon winds over the Arabian Sea and propagating swells from the SW. During the SW monsoon, the wave heights are typically higher compared to the rest of the season. The observed wave data for Shamal swells also show an increase in the wave height during the Indian SW monsoon with corresponding high energy. Because of the increase in wave height, the amount of energy carried by these swells is large during June and July compared to winter Shamal swells at the Indian coast. In May, the presence of a large number of waves coming from the NW direction due to summer Shamal winds will play an important role in the sea state of the northern Arabian Sea and near-shore circulation of the Indian coastline.

Table 3 shows the variation in the number of days of summer Shamal swells observed at Ratnagiri along the west coast of India. Observed summer Shamal swells show an increase during 2011 (43 days) compared to 2010 (30 days) due to the stronger summer Shamal winds in 2011 than 2010. The maximum observed summer Shamal swell was in May and showed a decrease in number as the SW monsoon reached the Indian subcontinent, and the observed summer Shamal swell was minimized in July due to the strong SW monsoon.

5. Conclusion

Wave data measured off Ratnagiri during the time of summer Shamal events (between May and August) in the Arabian Peninsula are analyzed, along with the ASCAT wind, NCEP data and AWS wind collected at Ratnagiri. The presence of a NW swell is identified at Ratnagiri along the west coast of India from the measured wave data. ASCAT data indicate the NW winds in the Persian Gulf during the study period. An analysis of swell and wind sea direction indicates the presence of swells from the NW direction during May and from the W-NW direction during the remaining months. The prevailing wind condition in the Arabian Sea influences the generation of wind sea in the region during the arrival of NW swells and shows the wind sea from the SW direction. The mean period of Shamal swells is in the range of 6.5-11.2 seconds during summer, whereas during winter, the mean wave period is in the range of 6-8 seconds. The significant wave height associated with the Shamal swells is high, and it reaches a maximum of 3.4 metres and is twice the wave height observed during the winter season. The passage of summer Shamal swells through the Arabian Sea is dependent on the strength of the SW Indian monsoon winds blowing over the Arabian Sea. The wind pattern over the west coast of India at Ratnagiri is driven by NW winds in May. However, during the summer monsoon, the wind pattern depends on the strength of the monsoon winds from the SW and summer Shamal winds from the NW.

Acknowledgements

The authors thank the Director, CSIR-NIO and the Director, INCOIS for providing facilities and encouragement. The authors also thank Mr. K. Ashok Kumar for help during the wave data collection and Mr. G. Udhaba Dora for help in preparation of Fig. 2. We thank Prof. Ramola Antao, Consultant, Senior Cambridge English examinations in India for editing the manuscript. This paper is NIO contribution No. ----.

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Table 1: Monthly variation of Peak wave period (Tp), Wave direction (Dp), Mean wave period (Tm), Significant wave height (Hs), Swell direction (Dswell), Sea direction (Dsea), Significant swell height (Hswell), Significant sea height (Hsea), Swell period (Tswell) and Sea period (Tsea) of NW swells during the SW monsoon (May- August) in 2010 measured off Ratnagiri at a depth of 13 metres.

Wave Parameters	May 2010			June 2010			July 2010			August 2010		
	Min	max	mean	min	max	mean	min	max	mean	min	max	mean
Tp (s)	4.6	8.3	6.8	9.1	11.1	10.5	6.67	12.5	9.4	6.7	10.5	9.6
Dp (^{o})	270	307	284	270	280	272	270	283	272	270	273	271
Tm (s)	3.9	6.1	5.1	5.4	7.7	6.6	5.2	7.5	6	5.7	6.9	6.4
Hs (m)	0.7	1.6	1.2	1.4	2.7	2.1	1.4	3.4	1.8	1.5	3.1	2.4
Dswell (^{o})	270	307	283	270	280	272	270	283	272	270	273	271
Dsea (^{o})	262	307	285	247	291	267	255	284	270	257	276	266
Hswell (m)	0.4	1.4	1.0	1.2	2.5	1.9	1.1	3.1	1.5	1.2	2.5	2.0
Hsea (m)	0.3	1	0.7	0.6	1.6	0.9	0.5	1.8	1.0	0.9	2	1.3
Tswell (s)	6.6	8.9	7.5	7.9	10.3	8.9	7.04	10.3	8.4	7.7	9.7	8.8
Tsea (s)	2.6	4.4	3.4	3.0	5.2	3.9	3.1	4.7	3.8	3.9	4.8	4.3

Table 2: Monthly variation of Peak wave period (Tp), Wave direction (Dp), Mean wave period (Tm), Significant wave height (Hs), Swell direction (Dswell), Sea direction (Dsea), Significant swell height (Hswell), Significant sea height (Hsea), Swell period (Tswell) and Sea period (Tsea) of NW swells during the SW monsoon (May- August) in 2011 measured off Ratnagiri at a depth of 13 metres.

Wave Parameters	May 2011			June 2011			July 2011			August 2011		
	min	max	mean	min	max	mean	min	max	mean	min	max	mean
Tp (s)	4.1	10	7.8	7.7	11.8	10.7	10	11.7	10.7	7.69	11.1	9.7
Dp (^{o})	270	307	287	270	287	272	270	274	271	270	276	271
Tm (s)	3.7	6.4	5.2	5.7	7.5	6.6	5.5	7.4	6.6	5.4	6.8	6.2
Hs (m)	0.7	1.7	1.1	1.5	3.1	2.5	1.8	2.5	2.0	1.6	2.9	2.3
Dswell (^{o})	270	308	286	270	287	272	270	274	271	270	276	271
Dsea (^{o})	257	308	283	239	287	261	233	276	256	232	280	264
Hswell (m)	0.3	1.4	.9	1.3	2.7	2.1	1.5	2.3	1.8	1.2	2.6	1.9
Hsea (m)	0.4	1.0	0.7	0.8	2.4	1.2	0.6	1.5	1.0	0.8	1.9	1.3
Tswell (s)	6.6	9.6	8.0	7.8	11.2	9.2	8.0	10.0	9.1	7.2	10.2	8.6
Tsea (s)	2.8	4.4	3.6	3.3	5.5	4.1	3.2	4.8	4.0	3.4	5	4.1

Table 3: Monthly percentage variation of summer Shamal swells observed at Ratnagiri during the SW monsoon of 2010 and 2011

Year	Months	No of Shamal days (Dswell >270^{o})	Monthly percentage
2010	May	16	51.6
	June	6	20.0
	July	4	12.9
	August	4	12.9
2011	May	19	61.3
	June	10	33.3
	July	5	16.1
	August	9	29.0

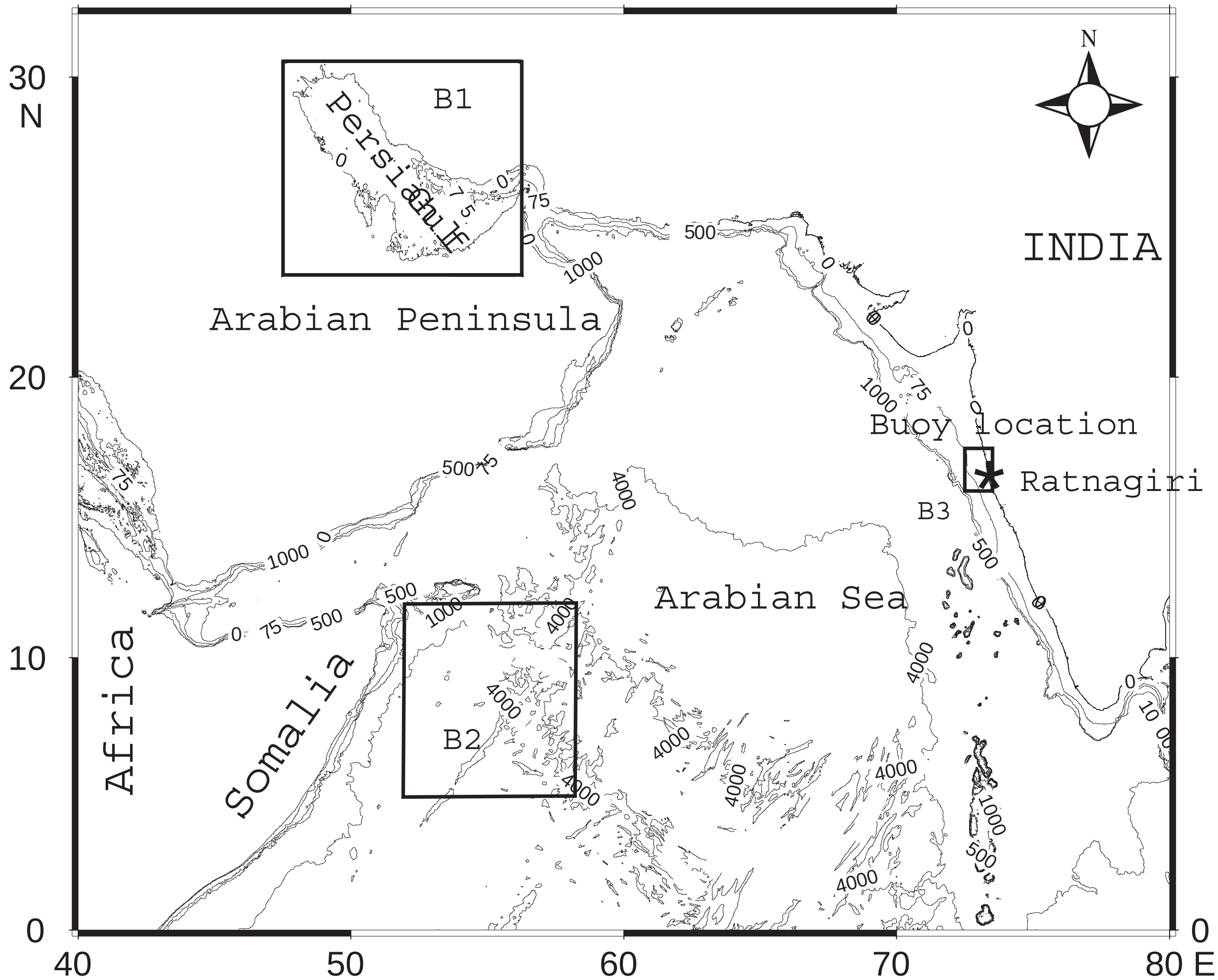


Figure 1. Study area showing the wave measurement buoy location. The depth contours are in metres.

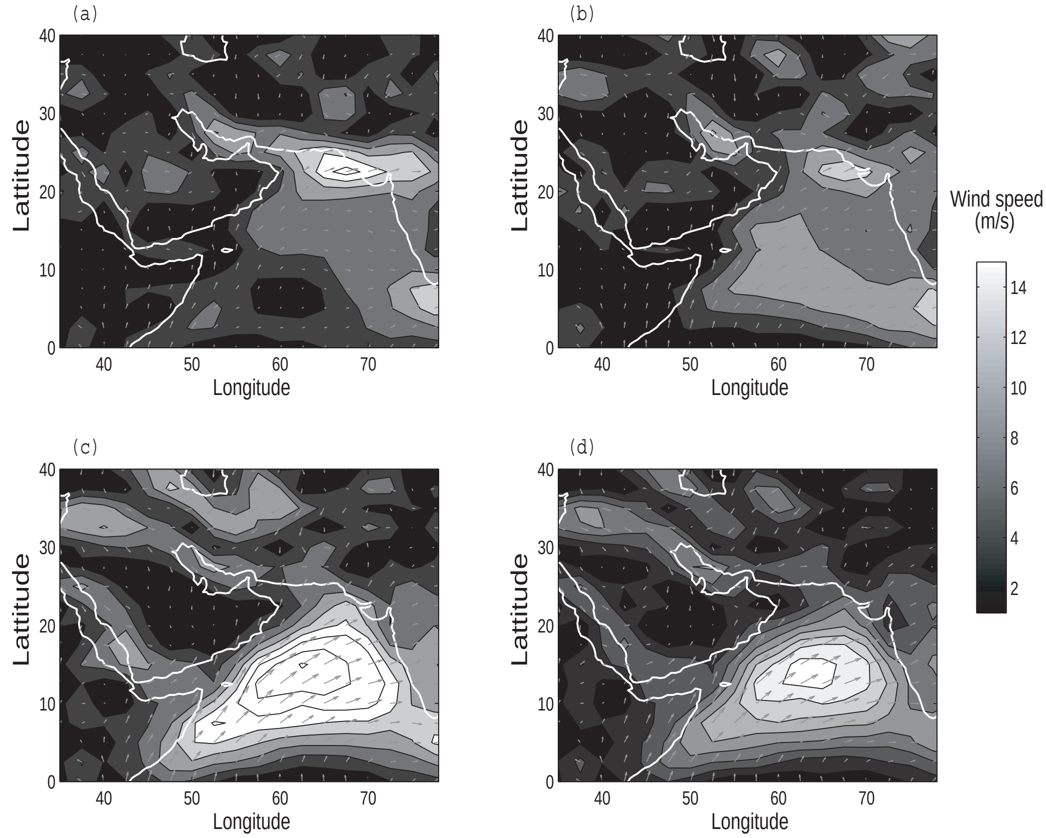
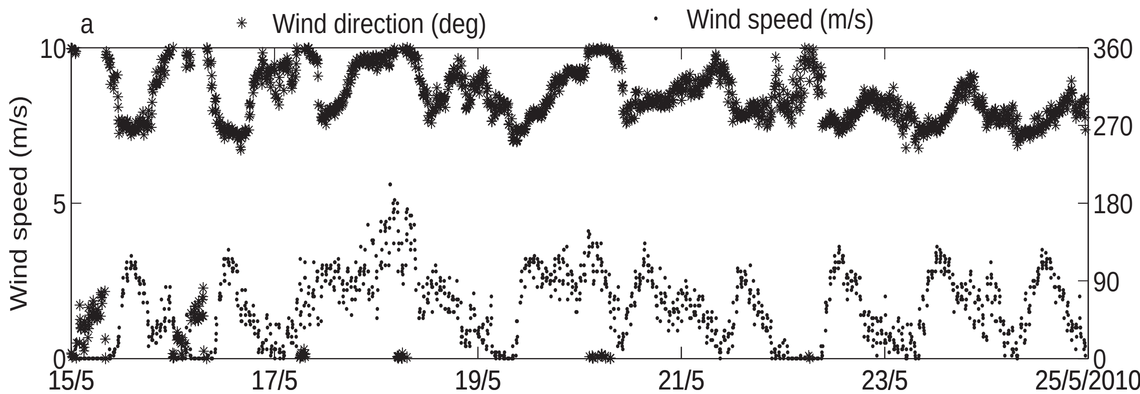


Figure 2. Composite average map of wind speed and wind direction during weak SW winds and strong summer Shamal (NW) winds (a) in 2010 and (b) 2011 and during strong SW winds and weak summer Shamal (NW) winds (c) in 2010 and (d) 2011



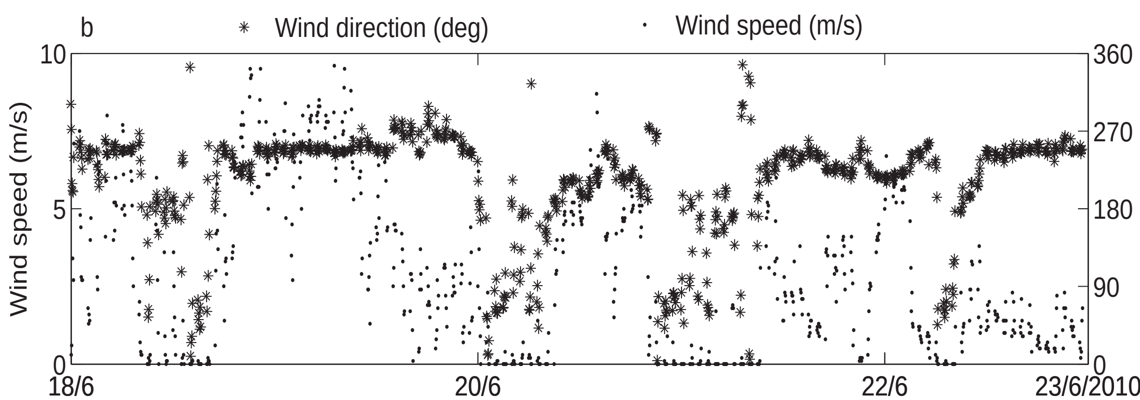


Figure 3. Measured AWS wind direction and wind speed at Ratnagiri during (a) May and (b) June 2010. The meteorological convention is used for presenting the data (0 and 360° for wind from North, 90° for East, 180° for South and 270° for West).

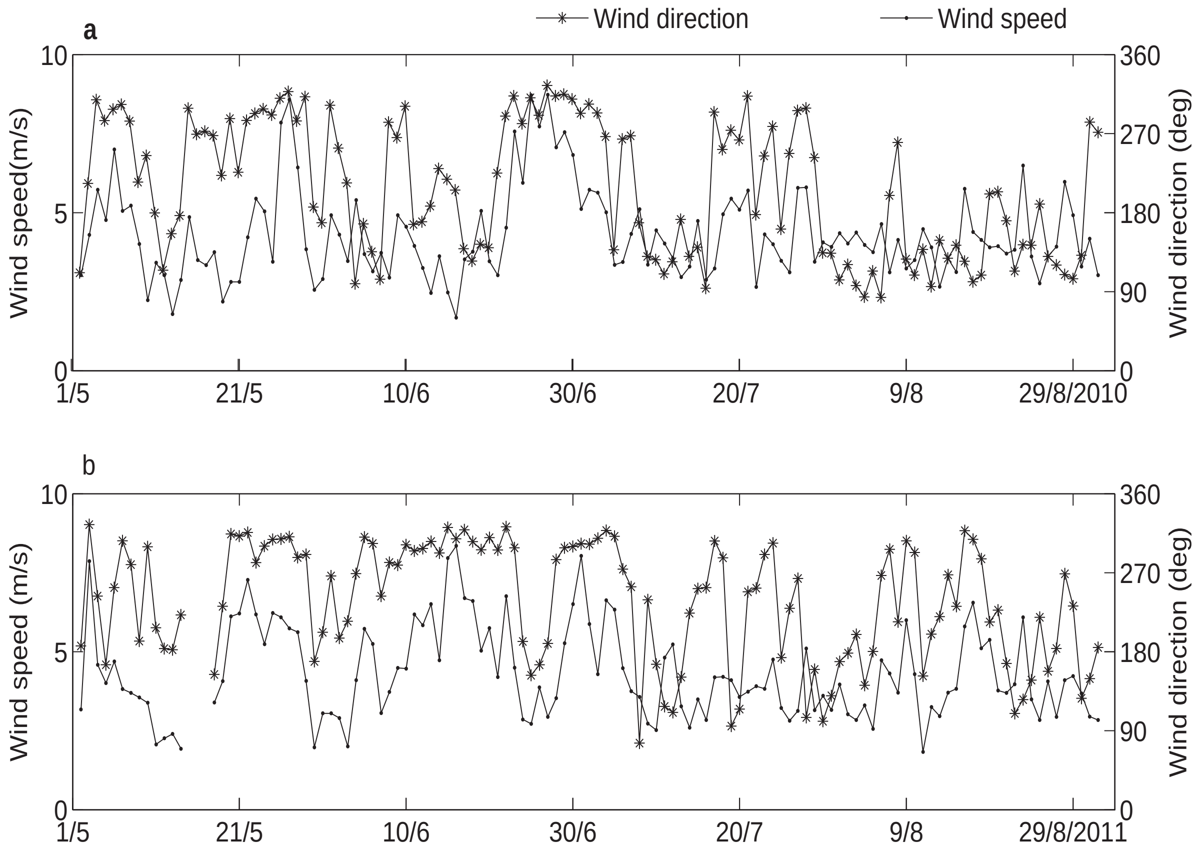


Figure 4. ASCAT wind direction and wind speed at the Persian Gulf during (a) 2010 and (b) 2011

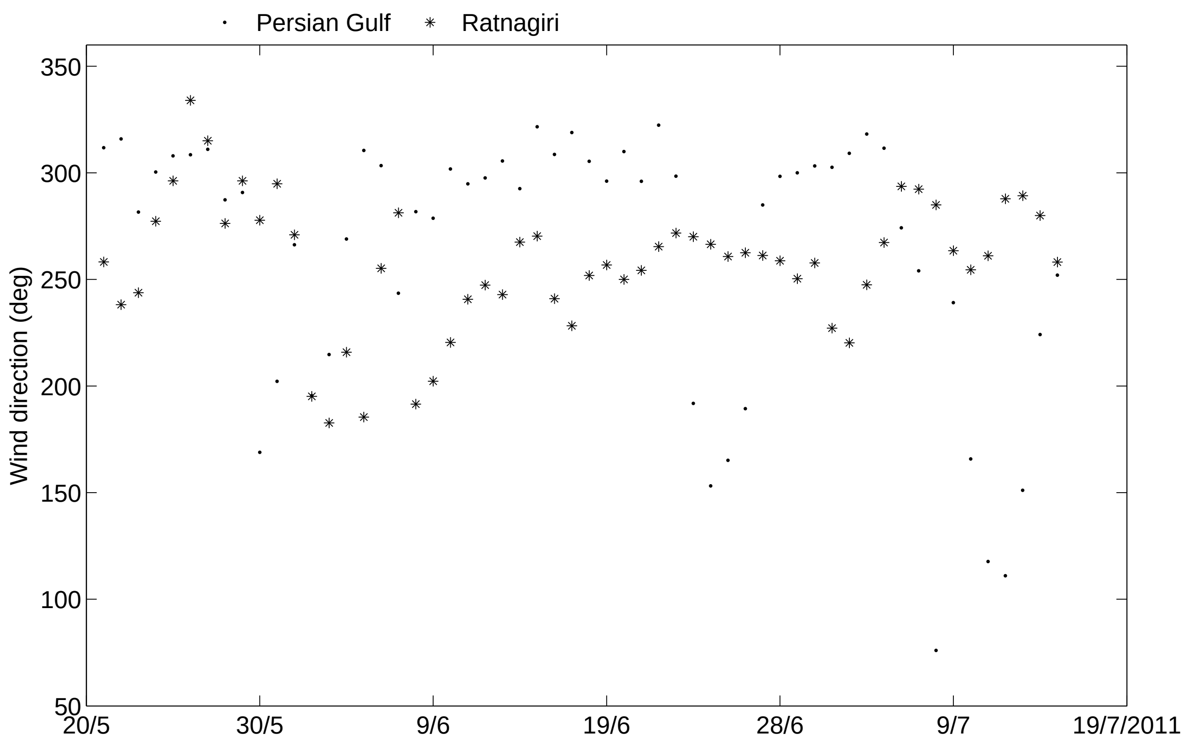


Figure 5. ASCAT wind direction at the Persian Gulf and Ratnagiri along the west coast of India from May 20 to July 19, 2011.

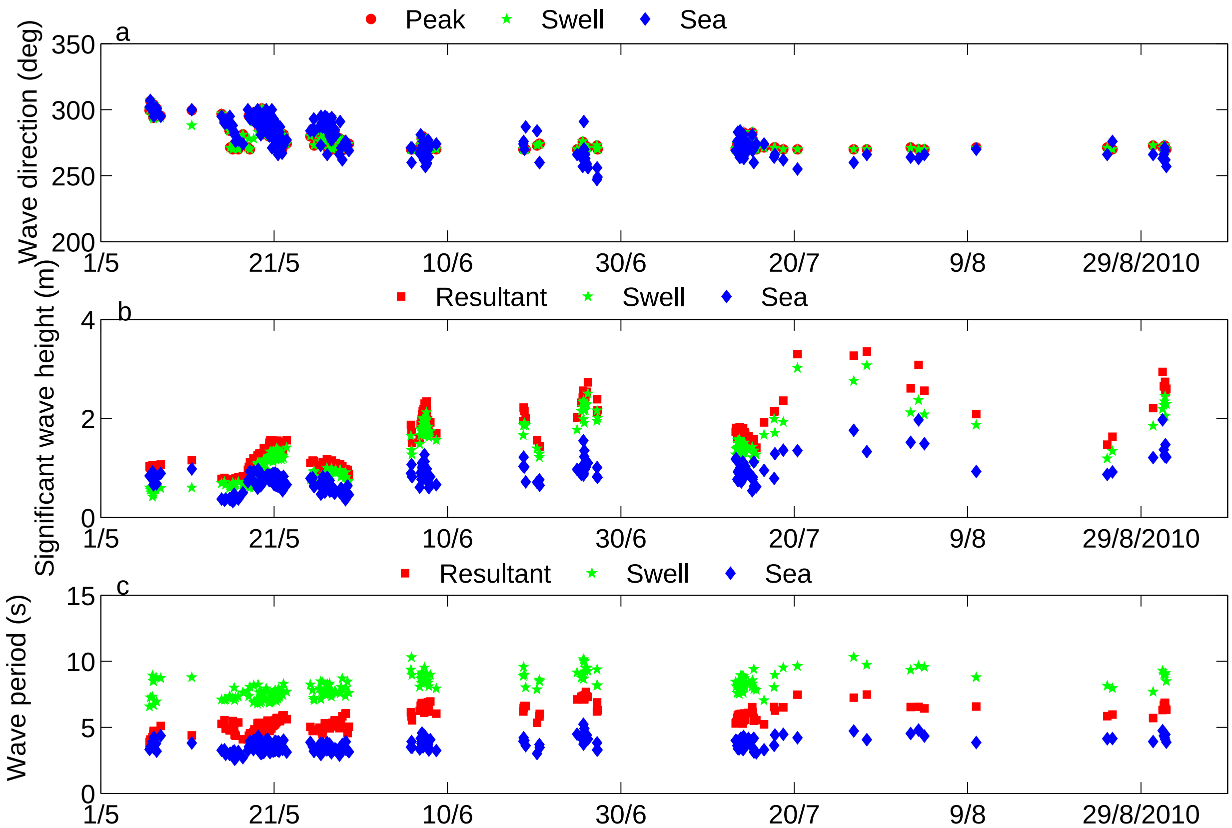


Figure 6. (a) Wave direction, (b) significant wave height and (c) wave period of sea, swell and resultant of northwesterly summer Shamal swells in 2010. Peak is the dominant direction value without separating into sea and swell. Sea and Swell indicate the wave characteristics of sea and swell component. Resultant is the estimated value without separating into sea and swell.

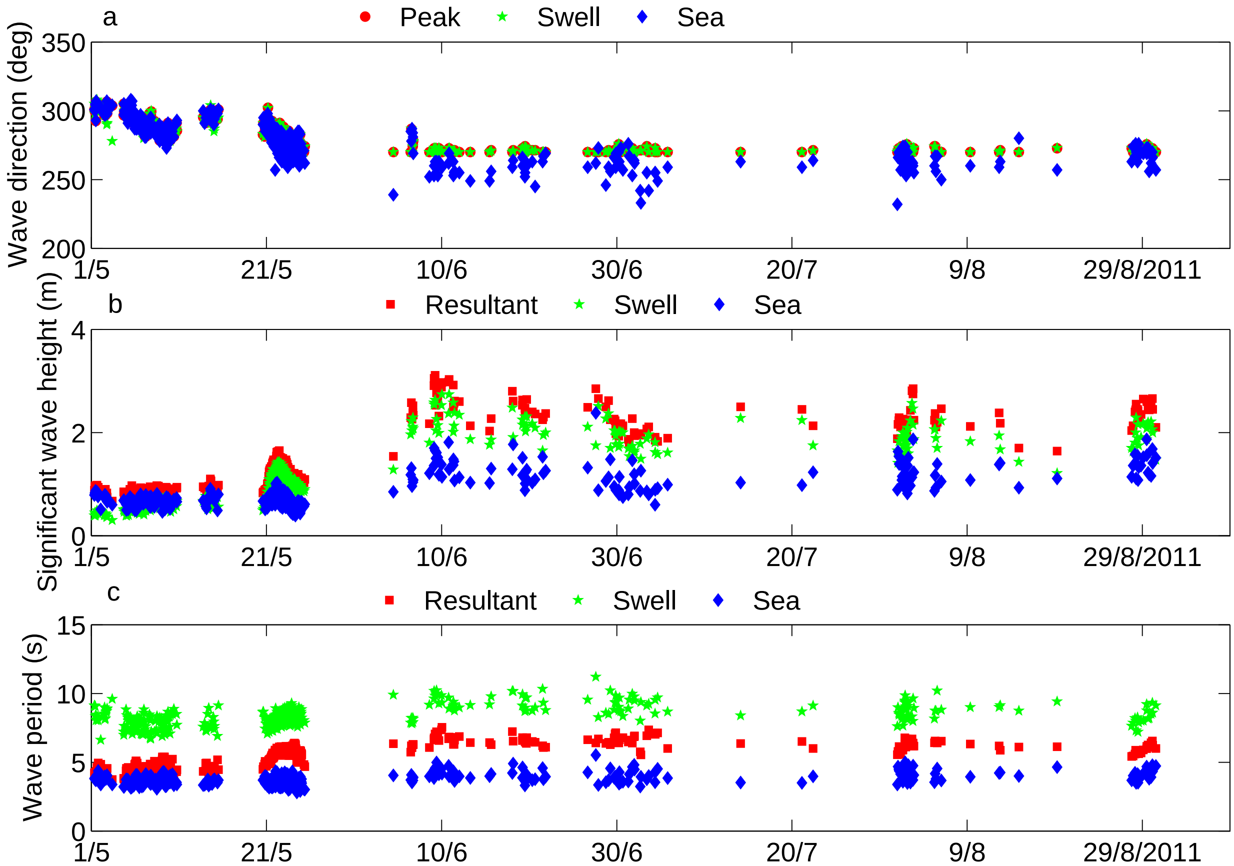


Figure 7. Wave direction, significant wave height and wave period of sea, swell and resultant of northwesterly summer Shamal swells in 2011. Peak is the dominant direction value without separating into sea and swell. Sea and Swell indicate the wave characteristics of sea and swell component. Resultant is the estimated value without separating into sea and swell.

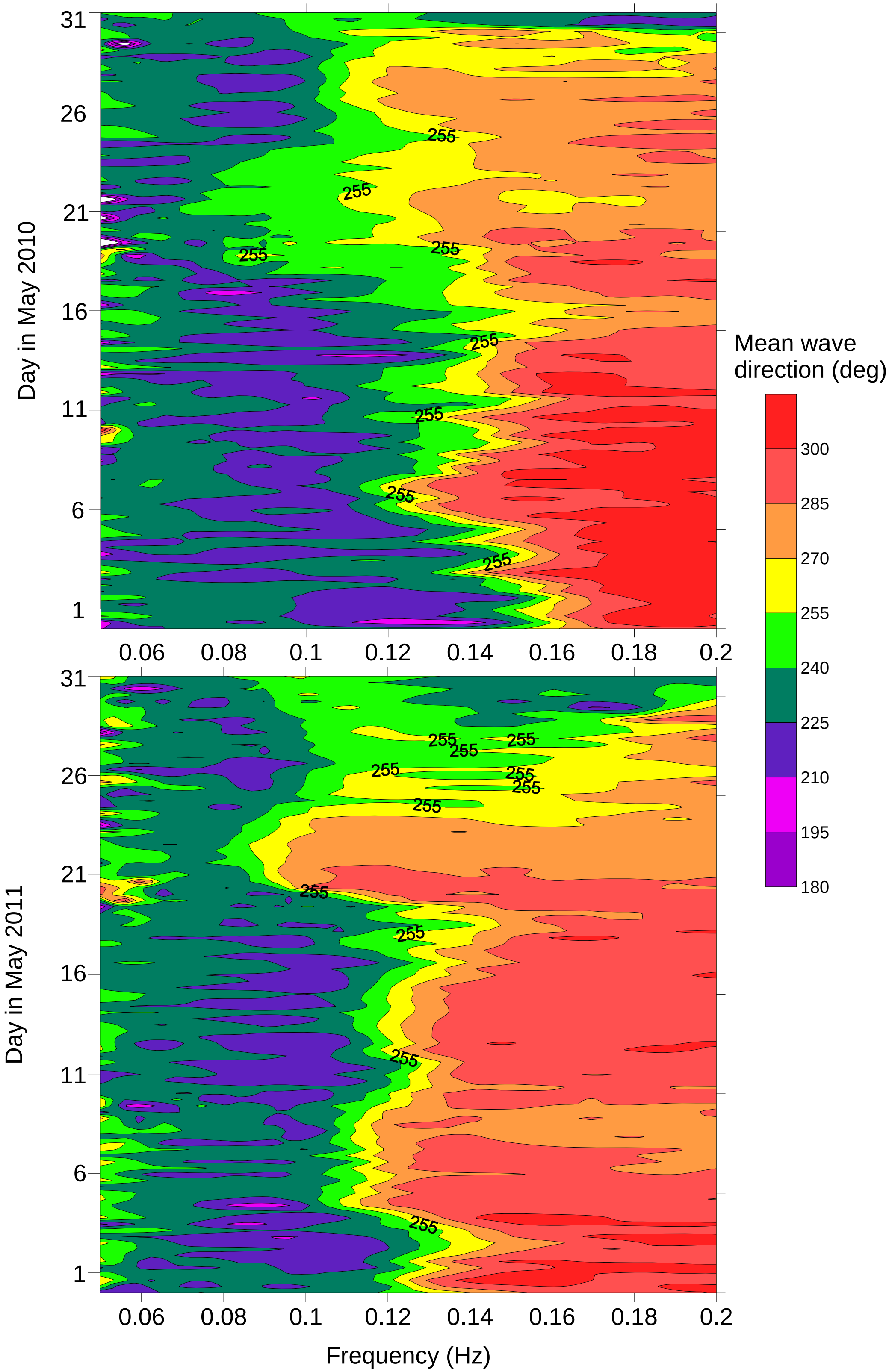


Figure 8. Wave direction contours on a Frequency–time domain for the month of May during 2010 (top) and May 2011 (bottom).